Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry

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The retrieval of ocean color radiometry from space-based sensors requires on-orbit vicarious calibration to achieve the level of accuracy desired for quantitative oceanographic applications. The approach developed by the NASA Ocean Biology Processing Group (OBPG) adjusts the integrated instrument and atmospheric correction system to retrieve normalized water-leaving radiances that are in agreement with ground truth measurements. The method is independent of the satellite sensor or the source of the ground truth data, but it is specific to the atmospheric correction algorithm. The OBPG vicarious calibration approach is described in detail, and results are presented for the operational calibration of SeaWiFS using data from the Marine Optical Buoy (MOBY) and observations of clear-water sites in the South Pacific and southern Indian Ocean. It is shown that the vicarious calibration allows SeaWiFS to reproduce the MOBY radiances and achieve good agreement with radiometric and chlorophyll *a* measurements from independent *in situ* sources. We also find that the derived vicarious gains show no significant temporal or geometric dependencies, and that the mission-average calibration reaches stability after ~20–40 high-quality calibration samples. Finally, we demonstrate that the performance of the vicariously calibrated retrieval system is relatively insensitive to the assumptions inherent in our approach.

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1. Introduction

Satellite ocean color data records provide the research community with a means of studying the Earth's marine biosphere on spatial and temporal scales unattainable via conventional *in situ* methods. The sea-viewing wide field-of-view sensor (SeaWiFS [1]) and moderate resolution imaging spectroradiometer flying on the Aqua spacecraft (MODIS-Aqua [2]), for example, have supplied global marine bio-optical data since 1997 and 2002, respectively. The community relies on these data to support studies ranging from regional ecosystem monitoring to the development of global climate records.

Space-based ocean color sensors measure the radiance exiting the top of the atmosphere (TOA) at a number of discrete wavelengths, λ, generally spanning the visible and near infrared (NIR) spectral regime. An atmospheric correction algorithm (e.g., Gao *et al.* [3], Antoine and Morel [4], Gordon and Wang [5]) is required to retrieve the portion of that TOA radiance signal, $L_t(\lambda)$, that is associated with radiance upwelled from beneath and transmitted through the sea surface. The desired uncertainties on this water-leaving radiance retrieval, $L_w(\lambda)$, however, cannot be achieved through instrument calibration and characterizations alone [6]. For example, the prelaunch calibration uncertainties for SeaWiFS are approximately 3% of the $L_t(\lambda)$ signal [7]. In a typical open-ocean scenario of oligotrophic waters, where the absorption of blue light is minimal, $L_w(\lambda)$ contributes ~10% to the total signal at the TOA in the blue-green spectral regime (i.e., 412 to 555 nm). As such, the 3% uncertainty in the prelaunch calibration approaches 30% on $L_w(\lambda)$, which is well above the stated goal of 5% for the L_w retrieval at 443 nm, $L_w(443)$ [8]. To retrieve water-leaving radiances with sufficient fidelity for climate and ecosystem research, satellite ocean color sensors require additional on-orbit calibration [6].

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The Ocean Biology Processing Group (OBPG) at NASA Goddard Space Flight Center is responsible for the operational processing of ocean products from SeaWiFS, MODIS, and other ocean color capable sensors. In the vicarious calibration process developed by the OBPG, multiplicative correction factors are derived that force the instrument response at each sensor wavelength, in combination with the atmospheric correction algorithm, to retrieve expected values of $L_w(\lambda)$. During operational data processing, these gain factors are applied to $L_t(\lambda)$, effectively updating the prelaunch and onboard instrument calibration to account for characterization errors or undetermined postlaunch changes in response, as well as any systematic bias associated with the atmospheric correction algorithm. In this paper, the operational vicarious calibration approach employed by the OBPG is described in detail. Following that, we present results for the calibration of the SeaWiFS mission and investigate the sensitivity of those results to various assumptions within our approach.

6. Conclusions

For satellite-borne ocean color sensors, we defined the vicarious calibration as the set of gain factors that, when applied to the observed TOA radiances, force the combined instrument response and atmospheric correction process to reproduce the expected water-leaving radiance at the sea surface. The vicarious calibration approach we described is independent of the source of the expected water-leaving radiance, but it is strictly specific to the atmospheric correction algorithm and relative to the instrument calibration.

We showed that the operational vicarious calibration of SeaWiFS, targeting two sites in the South Pacific and southern Indian Ocean to calibrate the NIR bands and MOBY measurements to calibrate the visible bands, enables the satellite sensor + algorithm system to accurately reproduce the water-leaving radiances from MOBY and significantly improves the quality of ocean color retrievals relative to globally distributed open-ocean field measurements. Furthermore, the calibration gains were shown to be stable over time and over the range of viewing and solar geometries encountered at the calibration sites, suggesting that the instrument prelaunch characterization, temporal calibration, and atmospheric correction model are correctly compensating for changes in the instrument and variations associated with radiant-path geometry. In addition, the mean vicarious gains were found to stabilize to within 0.1% of the final values after approximately 20–40 high-quality calibration samples, which provides some indication as to the extent of on-orbit calibrations that may be required by future missions to achieve similar quality in ocean color retrievals.

We also demonstrated that the ocean color retrievals are relatively insensitive to the NIR calibration (i.e., both the 765- and 865-nm bands of SeaWiFS) that governs the determination of aerosol contributions. This occurs because the vicarious calibration of the visible bands will tend to compensate for bias and spectral skew associated with the aerosol radiance retrievals, provided that the calibration process is internally consistent. In the OBPG approach, the visible bands are calibrated relative to the NIR bands, with the shorter NIR band calibrated relative to the longer NIR band, and all vicarious calibrations are performed relative to the exact same atmospheric correction algorithm and instrument calibration used for the retrieval of normalized water-leaving radiance from observed TOA radiance. It follows that, if the atmospheric correction process is altered in any way, the vicarious calibration must be regenerated to maintain consistency. In fact, the OBPG routinely rederives the vicarious calibration from the same set of MOBY and NIR targets when testing the performance of algorithm changes such as alternate aerosol model suites or modified bidirectional reflectance formulations. Similarly, the vicarious calibration is intimately tied to the instrument calibration. For example, it is likely that the OBPG will update the SeaWiFS prelaunch calibration prior to the next major reprocessing, based on the findings of Barnes and Zalewski [40], and the vicarious calibration will have to be recomputed relative to that revised instrument calibration. It follows that the vicarious gains produced by the OBPG for ocean color processing of SeaWiFS, MODIS, and other ocean color sensors are only valid for the operational atmospheric correction algorithm and instrument calibration.

For all ocean color sensors supported by the OBPG, the operational vicarious calibrations were derived using open-ocean calibration targets and typical maritime atmospheric conditions. Considering that the vicarious calibration will absorb systematic bias in the atmospheric correction algorithm, it should be recognized that a set of fixed multiplicative factors cannot adjust for algorithm deficiencies over the full range of oceanic and atmospheric conditions and radiant-path geometries associated with global observations, as any error in the atmospheric correction model is not likely to be fractionally constant relative to the TOA radiances. As the observation conditions deviate from the nominal conditions and geometries of the vicarious calibration targets, the ability of the vicarious calibration to compensate for algorithm error will be diminished. For example, in some coastal and inland waters, the typical aerosol may not be well represented by the operational aerosol model suite or model selection process. Similarly, these more complex cases may trigger components of the atmospheric correction algorithm that are rarely exercised over open oceans, such as the correction for nonzero L_w(NIR) in turbid or eutrophic waters [20]. As such, until perfect algorithms exist, it may be necessary to perform regionally specific vicarious calibrations to obtain accurate ocean color retrievals in coastal and inland waters. The vicarious gains derived by the OBPG are designed to optimize the fidelity of ocean color measurements in the deep oligotrophic and mesotrophic waters that comprise the vast majority of the world oceans.